Executive Summary

CHAPTER CONTENTS

BACKGROUND OF THE DFE FLEXOGRAPHY PROJECT

Flexographic Ink Options: A Cleaner Technologies Substitutes Assessment (CTSA) assembles and analyzes the technical research that was performed by the U.S. EPA Design for the Environment (DfE) Flexography Project. The findings of this research are of considerable interest to the flexographic industry, both in the wealth of details and as an overall view of this industry segment at a particular point in time. As far as is known, this study provides the most detailed analysis ever done on flexographic inks.

The partnership scoped and researched

- three ink systems (solvent-based, water-based, ultraviolet-cured)
- nine ink product lines (2 solvent-based, 4 water-based, 3 UV-cured), and five colors of ink, including both process and spot (line) colors, for a total of 45 individual ink formulations
- more than 100 chemicals belonging to 23 chemical categories
- three film substrates (clear low-density polyethylene, white polyethylene/ethyl vinyl acetate, and clear oriented polypropylene)

This CTSA document identifies

- results of 18 performance tests
- potential hazards and risks to worker health and the environment
- costs (related to purchase and use of the ink components, energy consumption, ink use, environmental compliance, and other regulatory aspects)
- other opportunities for environmental improvements in flexographic inks and printing practices
- highlights of federal regulations affecting the industry

To ensure that ink formulators, printers, and technical assistance providers will have access to this information, the partnership intends to make the entire CTSA available in both printed and electronic formats. For more information about documents and other materials related to this project, readers can also visit the EPA Flexography Project website: (http://www.epa.gov/dfe/flexography/flexography.html).

CTSA Considerations

The CTSA is intended to reflect the characteristics of printing inks under "real world" production conditions. Performance tests were printed on volunteer commercial presses, not on a tightly controlled experimental press. Worker health risks were determined based on conditions found in a typical printing facility, rather than those of an ideal workplace. Like any study with this goal, it may lack the statistical accuracy of a controlled experiment, but it offers practical results that may approximate those of a typical printer.

Flexography currently accounts for about 20 percent of U.S. printing industry output, and it is the world's fastest growing printing technology, with an annual growth rate of 6.3% in 1996. Especially well suited to printing on flexible and non-uniform surfaces (such as plastic films and corrugated board), flexography prints a wide range of products we all use, such as snack food and frozen food bags, labels for medicines and personal care products, newspapers, drink bottles, and cereal containers. States with the majority of flexographic facilities include California, Illinois, New York, North Carolina, Ohio, Pennsylvania, Texas, Wisconsin, Georgia, and New Jersey. Flexographic facilities are generally small; approximately 40% have fewer than 20 employees, and 70% have fewer than 50 employees. However, the industry is seeing a trend of mergers and acquisitions. As mergers cause firms to grow, the selections of ink by an individual company can have an increasingly significant effect.

In the mid-1990s, the DfE Program at U.S. EPA began working with flexographic printing industry representatives to identify an aspect of the flexographic printing industry with significant environmental concerns. Historically, most flexographic inks were solvent-based, had high levels of volatile organic compounds (VOCs), and contained a wide variety of pollutants. Although the industry has addressed environmental and health problems of inks through add-on pollution control devices, these have not resolved all concerns of human health and ecological risks.

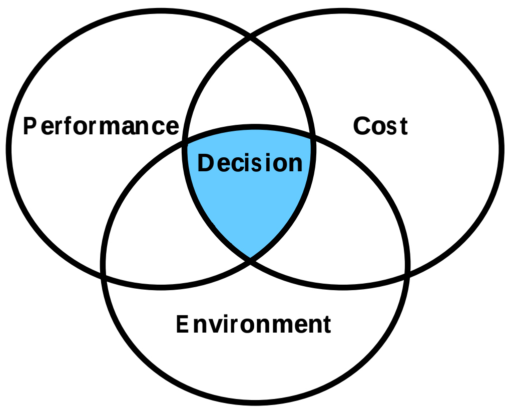
Therefore, the DfE Flexography Project, a voluntary partnership with industry, was established. The research project was initiated by representatives of flexographic trade associations, ink formulators, printers, suppliers to the printing industry, academic institutions, and EPA. The Project partners decided to focus on flexographic inks, which constitute a major cost category and have a variety of environmental and health issues. The Project's goals have been to work with the flexographic industry to understand the range of environmental and health impacts of flexographic inks, help flexographic professionals to select the cleanest inks that make business sense, and highlight opportunities for printers and formulators to take simple, useful actions that will improve operations and the environment.

Details about the process that was used to develop the CTSA can be found in Chapter 1 (Introduction). The methodology that was used to conduct the research is addressed in each relevant chapter.

The CTSA demonstrates that each of the flexographic ink systems and chemical categories studied may have health and environmental implications associated with their use. The results can help printers and formulators recognize these potential hazards and risks, and identify safer alternatives for some chemicals and chemical categories.

The Design for the Environment (DfE) Program

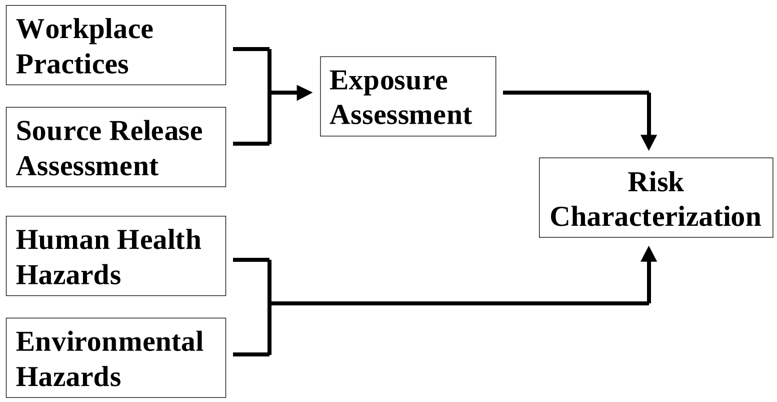
The Design for the Environment (DfE) Program is a voluntary partnership-based program between the U.S. Environmental Protection Agency (EPA) and various industries. Working with its partners, the DfE Program identifies cost-effective alternatives to existing products and processes that reduce risks to workers and the environmental while maintaining or improving performance and product quality. Thus, as shown in the diagram below, consideration of Performance, Cost, and Environmental Risk contribute to a Decision that is in the best interests of both the business and society. DfE serves as a catalyst for lasting change that balances business practicalities with sound environmental decision-making. A primary goal of DfE is to encourage pollution prevention rather than relying on end-of-pipe controls to reduce risks to human health and the environment.



POTENTIAL HAZARDS AND RISKS OF INK CHEMICALS

A risk assessment is a process that identifies chemicals that may present harm to humans and other organisms. Hazard identification seeks to determine whether a chemical *can* cause adverse health effects in humans or in nature. A dose-response assessment portrays the relationship between the dose of a chemical received and the incidence and severity of adverse health effects in the exposed population. An exposure assessment identifies populations that are or could be exposed to a chemical. A comparative risk characterization then uses all this information to develop quantitative and qualitative expressions of risk, for the purpose of comparing ink chemicals and ink systems. The methodology and findings of the risk assessment performed for flexographic inks are described in Chapter 3 and its appendices. Figure ES.1 shows the risk assessment process, and the box that follows shows the assumptions that the Project made about a “model facility” in developing the risk assessment.

Figure ES.1 The CTSA Risk Assessment Process



Model Facility Characteristics

- 4 presses
- 2 oxidizers
- 48" web
- 6 colors
- 500 fpm press speed
- 7.5 hr avg run length
- 22.5 production hours per day
- 300 production days per year
- 7,000 ft^3/minute ventilation rate

Release assumptions:

- 30% of volatile compounds released to air will be uncaptured emissions, 70% will be stack emissions
- solvent-based ink systems have a catalytic oxidizer with a 95% destruction efficiency

Exposure assumptions:

- Press and prep room worker exposure assumptions: 7.5 hour shift, 250 days/year
- Routine 2-hand contact with ink for dermal exposure; no gloves

Risk Analysis Considerations

- The results were based on the ink formulations as submitted to DfE. Reaction products or other changes in chemical composition resulting from the printing process (e.g., the curing process for UV-cured inks) were not considered.
- Hazard information for some chemicals was incomplete. Where hazard information was not complete, chemical hazard was assessed by considering the hazards of similar chemicals.
- Exposure and risk results are dependent on assumptions of how printing facilities are operated. For example, dermal results were calculated based on the assumption that no gloves are worn. If all workers consistently wear gloves when working with these chemicals, dermal exposure and risk would be substantially lower than reported here.
- In order to protect manufacturers' proprietary information, the risk section groups the specific chemicals in the ink formulations into chemical categories rather than presenting individual chemicals.
- Other factors that may affect risk, such as cleaning products, substrate composition, etc., were not considered in this analysis.
- Risk modeling was based on conditions expected in a "model facility." Key information about this facility are presented below. Other assumptions are described in Chapter 3. Under different assumptions, the results could potentially shift.

Aquatic Hazards

Over half of the more than 100 compounds studied in the flexography performance demonstrations showed a medium or high aquatic hazard concern. Eighteen chemicals were found to be of high aquatic hazard concern (see the box that follows). Another 34 chemicals were found to be of medium aquatic hazard concern. Because it was not expected that flexographic chemicals would be released to the aquatic environment, exposure assessments were not conducted, so risk characterizations for aquatic populations are not available. Therefore, it is possible that some or all of these chemicals could potentially pose risks to aquatic life if released to water bodies.

Chemicals of High Aquatic Hazard Concern

Amides, tallow, hydrogenated
Ammonia
C.I. Basic Violet 1 (molybdatephosphate and molybdatetungstenatephosphate)
C.I. Pigment Violet 27
Dicyclohexyl phthalate
Distillates, petroleum, hydrotreated light
2-Ethylhexyl diphenyl phosphate
Glycerol propoxylate triacrylate
n-Heptane
1,6-Hexanediol diacrylate
1-Isopropylthioxanthone
4-Isopropylthioxanthone
Mineral oil
Resin acids, hydrogenated, methyl esters
Styrene
Thioxanthone derivative
Trimethylolpropane ethoxylate triacrylate

A chemical with a high aquatic hazard is capable of causing long-term effects in aquatic organisms in a concentration of less than 0.1 mg/L.

Human Health Hazards

The CTSA identified three types of human health hazards: systemic toxicity, developmental toxicity, and carcinogenic (cancer-causing) hazards. Systemic toxicity refers to adverse effects on any organ system following absorption and distribution of a chemical throughout the body. Two chemicals used in the CTSA performance demonstrations (ethanol and silica) presented a high hazard, and twenty others presented a medium hazard. Many chemicals have not been studied thoroughly for environmental or health effects, hazards, or risks. Chemicals in UV-cured inks, perhaps because they are much newer, are much less likely than solvent- and water-based chemicals to have undergone in-depth testing.

Developmental toxicity refers to adverse effects on a developing organism that may result from as little as a single exposure prior to conception, during prenatal development, or postnatally up to the time of sexual maturation. The major manifestations of developmental toxicity are death, structural abnormality, altered growth, or functional deficiency. Four CTSA chemicals (barium, ethanolamine, isopropanol, and styrene) presented a high hazard, and four others presented a medium hazard.

Cancer hazards to humans of flexographic chemicals were also studied by the CTSA, and the following concerns were identified.

- Crystalline silica and ethanol have been determined to be carcinogenic to humans.
- Amorphous silica, isopropanol, polyethylene, polytetrafluoroethylene, propanol, C.I. Pigment White 6, kaolin, acrylic resin, two types of petroleum distillates (hydrotreated light and solvent-refined light paraffinics), and styrene fall into

various categories indicating potential for cancer concerns.

Human Health Risks

The hazard information for the flexographic ink chemicals was combined with estimated releases and exposures to arrive at risk characterizations for the ink systems and chemicals. The CTSA identified three types of human health risks: systemic toxicity, developmental toxicity, and carcinogenic risks. Risk estimates were modeled for both press and prep room flexographic workers and the general population living near a facility.

Overall, several systemic and developmental toxicity risks were identified, but no significant cancer risks were found. Although some inks contained chemicals with carcinogenic concern, these chemicals cause cancer through pathways that are not relevant to flexographic workers (e.g., through eating or breathing dust).

The risk posed by ink system will vary depending upon:
- specific chemical components of inks
- use and handling of inks
- type of toxicity (systemic vs. developmental)
- exposure route (inhalation vs. dermal)

Community Risks
None of the flexographic chemicals posed a clear risk to residents living adjacent to a flexographic facility. Several formulations posed possible risk for inhalation, but no formulations posed dermal risk because no dermal exposure to the general population was anticipated. Possible risk was posed by some solvents in solvent-based and water-based inks, and by some monomers and other chemicals in UV-cured inks. The risk assessment also found that exposure from solvent-based inks is expected to be higher than that from the other two systems despite the use of an oxidizer with the solvent-based system. At the minimum emissions capture efficiency (70%), the high rate of volatile emissions outweighs the decrease in emissions resulting from the pollution control equipment.

Worker Health Risks
Risk was assessed by modeling pressroom and prep room worker exposure. Each ink system was found to contain chemical categories with clear occupational health risks (see Tables ES.1 and ES.2). Alcohols, amides and nitrogenous compounds, and acrylated polyols were the chemical categories most often found to be of clear worker risk concern. For pressroom workers, exposure was highest with solvent-based inks because of their higher air release rate. The dermal exposure for both groups was found to be comparable for all three ink systems. Individual chemicals that were found to pose clear worker health risks are listed in the box (Toxicological Endpoints) following the tables.

Selected risk findings include the following points:

Overall:
- **Each ink system showed a considerable range among the formulations in the number of chemicals of concern** (2-4 for solvent-based, 1-4 for water-based, and 1-5 for UV-cured).
- **All ink systems had clear systemic and developmental risks to workers**.
- Some water-based and UV-cured inks were found to have fewer risk concerns than solvent-based inks.

- The use of press-side solvents and additives increased the occupational risk for many of the solvent- and water-based ink formulations. In particular, propanol and propylene glycol ethers in solvent-based inks, and ammonia, propanol, isobutanol, and ethyl carbitol in water-based inks presented clear or possible occupational risk in certain formulations.

Water-based inks:
- Amides or nitrogenous compounds in water-based ink formulations were common in presenting systemic risks to workers.
- Stack releases were calculated to be higher for some water-based inks compared to solvent, because oxidizers were not used with the water inks.

Solvent-based inks:
- Uncaptured emissions were higher for solvent-based inks. Oxidizers treat only captured stack emissions. Because pressroom workers can be exposed to uncaptured emissions, oxidizers did not appear to reduce the health hazards and risks for this group.
- Most of the chemical categories presenting a clear occupational risk in solvent-based ink formulations were solvents. The solvent-based inks released considerably more volatile organic compounds than the water-based and UV-cured inks.

UV-cured inks:
- Uncured UV inks posed a clear worker health risk via inhalation. Although chemical emissions from cured inks have not been tested, it is expected that curing greatly reduces the inhalation risks to workers compared to the risks presented in this report for uncured inks.
- Dermal exposure to UV inks also resulted in a clear worker health risk. The dermal risks associated with cured UV inks are not known.
- Acrylated polyols were the most prevalent category of clear risk in the UV-cured formulations, based on toxicological data.

Defining Risk Levels

Clear risk indicates that there is an inadequate level of safety for the chemical in question under the assumed exposure conditions, and that adverse effects can be expected. A chemical is placed in this category if it has a Hazard Quotient (HQ) (see Note 1 below) greater than 10, or a Margin of Exposure (MOE) (see Note 2) that is equal to or less than 10 or 100 (depending on the type of available data). If the chemical does not have a HQ or MOE, but instead was analyzed by the structure activity team (SAT), the chemical is considered to be of clear risk if it has a moderate or high hazard rating (see Note 3).

Possible risk indicates that the level of safety is slightly less than desirable and that the chemical may produce adverse effects at the expected exposure level. A chemical is designated as a possible risk if it has a HQ between 1 and 10, or a MOE that either is between 10 and 100 or 100 and 1,000. A SAT-analyzed chemical is of possible risk if it poses a low-moderate hazard (see Note 3).

Low or negligible risk indicates that there is an adequate level of safety at the expected exposure level. A chemical of low or negligible risk has a HQ less than 1, or a MOE that is greater than 100 or 1,000. An SAT-analyzed chemical is of low or negligible risk if it has a low hazard rating. (see Note 3).

Note 1. A Hazard Quotient (HQ) is the ratio of the average daily dose (ADD) to the Reference Dose (RfD) or Reference Concentration (RfC), where RfD and RfC are defined as the lowest daily human exposure that is likely to be without appreciable risk of non-cancer toxic effects during a lifetime. The more the HQ exceeds 1, the greater the level of concern. HQ values below 1 imply that adverse effects are not likely to occur.

Note 2. A Margin of Exposure (MOE) is calculated when a RfD or RfC is not available. It is the ratio of the NOAEL or LOAEL of a chemical to the estimated human dose or exposure level. The NOAEL is the level at which no significant effects are observed. The LOAEL is the lowest concentration at which effects are observed. The MOE indicates the magnitude by which the NOAEL or LOAEL exceeds the estimated human dose or exposure level. High MOE values (e.g., greater than 100 for a NOAEL-based MOE or greater than 1,000 for a LOAEL-based MOE) imply a low level of risk. As the MOE decreases, the level of risk increases.

Note 3. The SAT provided hazard levels based on analog data and/or structure activity considerations, in which characteristics of the chemicals were estimated in part based on similarities with chemicals that have been studied more thoroughly. SAT-based systemic toxicity concerns were ranked according to the following criteria: high concern — evidence of adverse effects in humans, or conclusive evidence of severe effects in animal studies; moderate concern — suggestive evidence of toxic effects in animals; or close structural, functional, and/or mechanistic analogy to chemicals with known toxicity; low concern — chemicals not meeting the above criteria.

Table ES.1 Clear Inhalation Risks for Flexographic Workers

Ink System	Chemical Categories of Clear Risk	Systemic Risk	Developmental Risk
Solvent-based	Alcohols	X	X
	Alkyl acetates	X	
	Hydrocarbons (low molecular weight)	X	
Water-based	Alcohols	X	
	Amides or nitrogenous compounds	X	X
	Ethylene glycol ethers	X	
UV-cured	Acrylated polyols	X	X
	Amides or nitrogenous compounds	X	X

See Defining Risk Levels box for definition of clear risk.

Table ES.2 Clear Dermal Risks for Flexographic Workers

Ink System	Chemical Categories of Clear Risk	Systemic Risk	Developmental Risk
Solvent-based	Alcohols	X	X
	Alkyl acetates	X	
	Inorganic pigments	X	X
	Organometallic pigments		X
	Organotitanium compounds		X
	Organic acids or salts		X
Water-based	Alcohols	X	X
	Amides or nitrogenous compounds	X	X
	Ethylene glycol ethers	X	
	Organic pigments	X	
	Organometallic pigments	X	
UV-cured	Acrylated polyols	X	X
	Acrylated polymers	X	X
	Amides or nitrogenous compounds	X	X
	Inorganic pigments		X
	Organometallic pigments	X	
	Organophosphorus compounds	X	

See Defining Risk Levels box for definition of clear risk.

Toxicological Endpoints of CTSA Chemicals with Clear Worker Health Risks

A total of 23 of flexographic ink chemicals (about 23% of the total) were found to pose clear worker health risks (See Defining Risk Levels box for definition of clear risk). The possible effects that are listed for each chemical are those that have been reported in the medical literature in association with use of the chemical. No inferences can be made from this list about possible exposure, doses, or severity of effects.

Alcohols, C11-C15-secondary, ethoxylated - skin irritant; eye irritation and lung effects

Ammonia - skin and eye irritation; corneal, liver, spleen, and respiratory effects

Ammonium hydroxide - skin irritation, eye effects, nasal irritation, respiratory effects

Barium - decreased body weight, increased arterial blood pressure, respiratory effects; developmental effects - reduced survival, decreased weight gain, blood effects

Butyl acetate - changes in serum chemistry, fluctuations in blood pressure; developmental effects - fetotoxicity, musculoskeletal abnormalities

Butyl carbitol - blood and skin effects, liver effects

CI Pigment Red 23 - blood, kidney, and stomach effects

D&C Red No. 7 - thymus, reproductive, and kidney effects, and changes in organ weights and clinical chemistry

Dipropylene glycol diacrylate (SAT) - genotoxicity, neurotoxicity, oncogenicity; developmental and reproductive effects; dermal and respiratory sensitization; skin and eye irritation

Distillates, petroleum, hydrotreated, light (SAT) - skin carcinogenicity; skin, eye, and mucous membrane irritation, carcinogenicity, genotoxicity, and narcosis at high doses

Ethanolamine - skin sensitizer; respiratory irritation; kidney, liver, neurotoxic, and respiratory effects

Ethyl acetate - general toxicity

Ethyl carbitol - decreased food consumption; bladder, blood, kidney, liver, spleen, and blood chemistry effects; altered organ weights; neurotoxic reproductive effects

Glycerol propoxylate triacrylate - tissue necrosis, decreased body weight, neurotoxic and respiratory effects

n-Heptane - auditory and neurotoxic effects, altered serum chemistry

Hydroxylamine derivative (SAT) - genotoxicity, dermal sensitization, developmental toxicity

Hydroxypropyl acrylate - respiratory effects

Isobutanol - blood and neurotoxic effects, changes in enzyme levels; reproductive effects - cardiac septal defects

Isopropanol - dermal sensitizer; blood and skin effects, tissue necrosis; kidney, liver, and spleen effects; respiratory effects; changes in enzyme levels and clinical and urine chemistry; developmental effects - fetal death, musculoskeletal abnormalities, fetotoxicity

Isopropoxyethoxytitanium bis (SAT) - neurotoxicity, genotoxicity, oncotoxicity, and developmental/reproductive toxicity. Skin, eye, mucous membrane irritant

Phosphine oxide, bis - skin sensitizer

Propanol - liver and reproductive effects (decreased fetal weight, malformations)

Trimethylolpropane triacrylate - decreased body weight; skin and neurotoxic effects; changes in clinical chemistry; altered organ weights; respiratory effects

Another 43 chemicals (about 43% of the total) were found to pose possible worker health risks.

PERFORMANCE

The CTSA used a combination of performance demonstrations at 11 volunteer facilities as well as laboratory tests at the Western Michigan University (WMU). The ink formulations were printed on three substrates: (1) clear low-density polyethylene (LDPE), (2) white polyethylene/ethyl vinyl acetate (PE/EVA), and (3) clear oriented polypropylene (OPP). These three substrates were chosen to allow a wide range of flexographic printers to benefit from the data analysis. The test image included process and line printing, to represent a wide range of types of flexographic printing. The performance demonstration runs also included both surface and reverse printing. All the inks/substrate samples collected in both the performance demonstrations and the laboratory runs were subjected to an extensive series of tests. A total of 18 different tests were conducted to analyze a wide range of ink properties and inks' effects on substrates, focusing on aspects that would be important to many flexographic printers. The tests (listed alphabetically in Table ES.3) measure many aspects of appearance, odor, and durability of the inks, as well as evidence of interactions between the inks and film substrates. Some of these tests have established quality standards, whereas many do not. The performance test methodology and results are shown in detail in Chapter 4 and its appendices.

Table ES.3 Performance Tests Conducted on CTSA Inks

Test Name	Purpose
Adhesive lamination	Measures bond strength between the adhesive layer of the lamination and the ink. In laminations, the ink needs to bond well to both top and bottom lamination structures.
Block resistance	Measures the bond between ink and substrate when heat and pressure are applied. Ink transfer from a printed substrate to a surface in contact with the print indicates that blocking has occurred.
CIE L*a*b*	Measures the reflected light of a printed color and calculates a unique numerical value. The ability to match L*a*b* values is crucial in producing high-quality graphics and meeting customer specifications.
Coating weight	Measures the weight of the ink film layer on a substrate after drying; affects all final printed properties, both optical and physical.
Coefficient of friction (COF)	Determines the resistance of a printed object to sliding. High COF is important is some situations, low COF in others.
Density	Measures the degree of darkness (light-absorption) of a printed solid.
Dimensional stability	Measures how printing conditions distort the linear dimensions of the substrate. Various factors, such as heat from the dryers, can affect stability by changing the physical dimensions of the substrate — in either the cross-web direction (perpendicular to the movement of the web) or the machine direction (the direction in which the web moves).
Gloss	Measures the reflection from a light source directed at the surface from an angle.
Heat resistance/ heat seal	Measures the degree to which a printed substrate will resist transfer when heated. Many printed products are subjected to extreme heat during handling and storage.

Ice water crinkle adhesion	Measures the integrity and flexibility of the ink on the substrate when exposed to refrigerator and freezer conditions. Many flexographically printed products, such as those used for frozen foods, are subjected to very cold conditions. The inks must stay flexible and maintain the integrity of their adhesion to the substrate under these conditions so that they don't rub off or flake off.
Image analysis	Measures how well the image is formed. Good image detail is important for printing, particularly for small type, reverse type, and halftones (single or process color).
Jar odor	Measures the type and strength of odor produced by ink film on the substrate. Many flexographically printed products are used for food packaging, so it is important that ink odor does not affect the packaged product.
Mottle/lay	Measures spottiness or non-uniformity of an ink film layer. Minimizing mottle is important for high-quality printing.
Opacity	Measures the percentage of light blocked from being transmitted through the ink film and substrate. The opacity values indicate the uniformity of ink coverage of the substrate. Opacity is critical on clear substrates, where an opaque background is needed to provide a backdrop for other color graphics.
Rub resistance	Indicates the ink's ability to resist being rubbed off substrate. Dry rub resistance is critical on products such as retail bags and bread bags, as the exposed ink film is abraded and scuffed during end use. Wet rub resistance is very important on frozen food bags, which can be subjected to abrasion during handling.
Tape adhesiveness	Measures the bond of the dry ink to the substrate. Adequate ink adhesion is critical; if the ink doesn't adhere well enough, it will not be able to stand up to the normal demands placed on the finished product.
Trap	Measures how well one ink prints on top of another. Good trapping is necessary to ensure adequate overprinting and to produce the desired color hue.
Uncured residue (UV-cured inks only)	Measures whether uncured residue from UV-cured ink remains on the printed substrate after the final UV curing station. Uncured ink may have possible negative results, such as odor, ink transfer to the rollers, and ink contact with food after packaging.

Substrate type played a major role in performance, especially for UV-cured inks, showing that the ink-substrate relationship is very important to the performance of printed products. In fact, the results varied widely among tests for each ink system. No one test can provide a reliable or accurate indicator of overall quality for any printer. When determining which type of ink system will be most appropriate for the facility, printers need to consider the needs of their clients, the type of substrates and products that they most often print, the desired aspects of quality that are most critical, cost, health and environmental risks, energy use, and pollution prevention opportunities.

Some general conclusions that can be drawn from the performance analysis include the following:

- No clear evidence emerged from these tests that either the solvent-based or the water-based system performed better overall.
- Many tests results showed wide variability.

- A flexographic printer cannot assume that any of these ink systems or ink-substrate combinations will be best-suited to the firm's overall needs. Careful testing of a potential ink system on the various substrates that a printer will be using most often is critical to obtaining desired quality on a consistent basis.

Table ES.4 lists ink system, color, and substrate combination with "best in class" performance for selected tests that were run. It is important to keep in mind that most tests do not have industry standards, and for some tests the determination of a better or worse result can depend on the needs of a specific printing situation. Also, not all systems received all tests. Therefore, these results point to the wide diversity of findings rather than to any possible superiority of a particular ink system, substrate, or formulation. The "worst" score is also provided, only to give an indication of the large range in scores on almost all tests. For details on these and the other performance tests, see Chapter 4.

Table ES.4 "Best in Class" Performance on Selected CTSA Tests

Test	Best Score	Ink System	Substrate	Color	Worst Score[a]
Adhesive lamination	.3040 kg	solvent	OPP	N/A	.2575 kg
Block resistance	1.0	UV no slip	LDPE	N/A	3.2
Density	2.17	UV high slip	LDPE	blue	1.09
Gloss	59.08	solvent	PE/EVA	N/A	32.31
Heat resistance	0 failures	solvent	OPP	N/A	24 failures
Ice water crinkle	0% removal	solvent water	LDPE, PE/EVA	N/A	36% removal
Image analysis	324 μm^2	solvent	PE/EVA	cyan	1050 μm^2
Mottle	47	UV no slip	LDPE	green	812
Rub resistance, wet	no failure	water	LDPE	green	failure at 2.2 strokes

[a]This score represents the other end of the range of all scores received on this test for all ink systems tested.

Performance Analysis Considerations

- The Partnership's Technical Committee and Western Michigan University selected 18 standard tests and designed a test image that included representative types of printing (e.g., text, blocks, and gradients).
- The substrates were selected to correspond to important flexographic product segments.
- Printing facilities volunteered to conduct the performance demonstrations.
- Performance demonstration inks were donated by ink companies. The inks were considered representative at that time.
- Because performance is a function of many factors — including equipment, ink, substrate, and operator experience — it is possible that a printer who conducted its own performance tests would have different results than the CTSA.
- Ink manufacturers are continually improving their inks, and new formulations on the market today may yield improved performance.

COSTS

Table ES.5 lists the average CTSA cost results for each ink system. Costs of materials, labor, capital (new press or retrofit) and energy, as well as regulatory, insurance, and storage costs, are discussed in detail in Chapter 5. These costs were based on ink consumption and energy use assumptions presented in Chapter 6.

For this analysis, the cost of inks and additives proved to be the second highest cost category (behind substrate). Because this was a short-term demonstration, the efficiencies of a long run with familiar products were not realized. Press speed under actual printing conditions is expected to be substantially different (and in general, higher) than in this analysis. However, generally speaking, press speed appears to be the most important cost driver, and thus a critical variable in maximizing profitability of flexographic printing, because all costs except that of ink and substrate are dependent on press speed. Therefore, if a facility can run one ink system (or one formulation) notably faster than another while meeting product quality standards, the faster system or formulation will probably also be the most cost-effective system.

Table ES.5 Cost Averages (per 6,000 square feet, at 500 feet per minute)

Ink system	Materials (Ink & Additives)	Labor	Energy	Capital	Total
Solvent-based	$15.29	$5.29	$0.53	$11.87	$32.98
Water-based	$9.55	$5.29	$0.35	$11.41	$26.60
UV-cured	$18.63	$5.29	$1.03	$11.87	$36.82

As the table shows, water-based inks had the lowest material costs. Water-based inks were consumed at a lower rate than solvent-based ink and had a lower per-pound cost than UV-cured. This system also had the lowest energy cost, due partly to the fact that no oxidizer, which combusts emissions at high temperatures, was used. Water-based inks had the lowest capital costs, because the presses usually did not have pollution control equipment or UV curing lamps. Therefore, at a press speed of 500 feet per minute, water-based inks were the least expensive. If an oxidizer were used with water-based inks (as is required in some areas), much of the cost savings would disappear.

Solvent-based inks had the highest capital costs because of the expense of oxidizers, and thus the total cost for this ink system was substantially higher than the water-based system. UV-cured inks had the highest energy costs because only electricity was used for this system, whereas the other two systems used a large percentage of less expensive natural gas. UV also had the highest material costs because of the higher per-pound cost of UV inks.

Cost Analysis Considerations

- Clean-up and waste disposal costs were not included in the quantitative analysis.
- The print run conditions may affect the level of ink maintenance, and therefore ink costs, more significantly than was demonstrated at the volunteer sites.

RESOURCE USE AND ENERGY CONSERVATION

The methodology and findings for ink and energy consumption in the CTSA are detailed in Chapter 6. Table ES.6 lists the energy use and estimated overall emissions from each ink system.

Table ES.6 Average Energy Consumption (at 500 feet per minute)

Ink System	Energy Consumed per 6,000 ft^2 (Btu)[a]	Emissions Generated (g/6000 ft^2)
Solvent-based	100,000	10,000
Water-based	73,000	6,800
UV-cured	78,000	18,000

[a]Electrical energy was converted to Btus using the factor of 3,413 Btu per kW-hr.

These energy estimates were used in the cost calculations for Chapter 5. Because the water-based ink systems did not use an oxidizer, their energy consumption was lower than for solvent-based inks or UV-cured inks. Much of the energy for the water-based system was derived from natural gas, which releases less emissions per unit of energy than does electricity. Thus, the environmental emissions due to energy production were also lowest for water-based inks.

UV-cured inks consumed less energy than solvent-based inks but were estimated to result in the highest energy-related emissions, because all energy for this system comes from electricity. Electricity generation and consumption are less efficient than the direct use of oil or natural gas. (See Tables 6.19 and 6.20 for details.)

Resource Use Analysis Considerations

- Ink consumption was calculated during the performance demonstrations by recording the amount of ink added to the press and subtracting the amount removed during cleanup. Several site-specific factors affected the calculated ink consumption figures: type of cleaning equipment, anilox roll size, and the level of surface tension of the substrate.
- The energy consumption analysis only considered equipment that would differ among the ink systems. Therefore, drying/curing equipment is included, but substrate winding equipment and ink pumps are not.
- Pollution estimates were developed using a computer model rather than by capturing and analyzing actual emissions from the facilities.

FEDERAL ENVIRONMENTAL REGULATIONS

This study is not regulatory in nature, and DfE is a non-regulatory program that operates on the basis of voluntary, multi-stakeholder partnerships. To provide additional useful information for the flexographic printing industry, however, the CTSA does include a basic overview of the major federal statutes that concern flexographic printers (see Chapter 2). Certain chemicals in the CTSA inks are specifically regulated by name under at least one federal statute (Table ES.7). In addition, many others are regulated as volatile organic compounds (VOCs).

A substantial number of the chemicals in the CTSA, however, remain unregulated under federal laws. Because many chemicals are not regulated and many have not been not tested for hazardous properties, printers may be unaware of the possible risks and hazards that accompany some chemicals.

Table ES.7 Major Federal Regulations Affecting Chemicals in the CTSA

Regulation	Affected Chemicals
Clean Air Act	
112(b) Hazardous Air Pollutant	Butyl carbitol Ethyl carbitol Styrene
112(r) Risk Management Plan	Ammonia (in concentrations greater than 20%)
Resource Conservation and Recovery Act (RCRA)	
Characteristic Wastes (D Wastes) (other chemicals than those shown here can also be characteristic wastes)	Barium (D005) Ethyl acetate (D001) Ignitable solvent-based inks (D001) Isobutanol (D001)
Non-specific Source Wastes (F Wastes)	Ethyl acetate (F003) Isobutanol (F005)
Specific Unused Chemicals (U Wastes)	Ethyl acetate (U112) Isobutanol (U140)
Toxic Substances Control Act (TSCA)	
Section 4	Butyl acetate Butyl carbitol Dipropylene glycol methyl ether Ethyl acetate 2-Ethylhexyl dephenyl phosphate Isobutanol n-Heptane
Section 8(a) PAIR	Ammonia Dicyclohexyl phthalate Dipropylene glycol methyl ether Isobutanol Isopropanol Ethyl acetate Ethyl carbitol 2-Ethylhexyl dephenyl phosphate n-Heptane 1,6-Hexanediol diacrylate Hydroxypropyl acrylate Propylene glycol methyl ether Silicone oil Styrene Urea

Section 8(d)	Dicyclohexyl phthalate Dipropylene glycol methyl ether Ethyl carbitol Ethyl acetate 2-Ethylhexyl diphenyl phosphate n-Heptane Isobutanol Isopropanol Propylene glycol methyl ether Silicone oil
Section 12(b)	Butyl acetate Butyl carbitol Dipropylene glycol methyl ether Ethyl acetate 2-Ethylhexyl diphenyl phosphate Isobutanol n-Heptane
Clean Water Act (CWA)	
Hazardous Substances (Reportable Quantities)	Ammonia (100 lbs.) Ammonium hydroxide (1000 lbs.) Butyl acetate (5000 lbs.) Styrene (1000 lbs.)
Priority Pollutants	Surfactants
Safe Drinking Water Act (SDWA)	
National Primary Drinking Water Regulations	Barium Styrene
Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)	
Reportable Quantities (RQs)	Ammonia (100 lbs.) Ammonium hydroxide (1000 lbs.) Butyl acetate (5000 lbs.) Butyl carbitol (RQ not listed) Dicyclohexyl phthalate (RQ not listed) Ethyl acetate (5000 lbs.) Ethyl carbitol (RQ not listed) Isobutanol (5000 lbs.) Styrene (1000 lbs.)
Emergency Planning and Community Right-to-Know Act (EPCRA)	
Extremely Hazardous Substances	Ammonia
TRI Chemicals	Ammonia (10% of total aqueous ammonia) Barium Butyl carbitol Ethyl carbitol Isopropanol Styrene

Occupational Safety and Health Act (OSHA)	
Personal Exposure Limits (PELs)	Ammonia Barium 2-Butoxyethanol Butyl acetate Dipropylene glycol methyl ether Ethanol Ethanolamine Ethyl acetate n-Heptane Isobutanol Isopropanol Kaolin Propanol Propyl acetate Styrene

CHOOSING AMONG FLEXOGRAPHIC INKS

As the CTSA makes clear, the choice of an ink system, an ink product line, or a specific ink formulation (color within a product line) is not a simple one, or one that should be based solely on any one aspect. Chapter 8 of the CTSA includes a table that provides an overall view of certain performance, cost, and resource use test results across all three ink systems (Table 8.2). The CTSA found that within each ink system, there was substantial variation in test results among individual product lines. Therefore, selecting the "cleanest" formulation within a system is just as important as selecting a system.

In addition to competitive aspects such as performance, cost, and energy use, inks also have important environmental health and safety implications. Every ink product line analyzed in the CTSA included chemicals that are associated with multiple clear health risks to flexographic workers (Table 8.3). Each ink system also was found to have safety hazards for the workplace (flammability, ignitability, reactivity, or corrosivity concerns). All of the formulations released VOCs and sometimes HAPs as well (Table 8.4).

Each of these aspects of ink use is associated with costs and benefits for both individual flexographic printing facilities and the larger society in which they function. These implications, which do not often enter in a printer's decision-making process, can be significant.

CONCLUDING REMARKS

Flexography is a thriving and rapidly expanding industry. As flexography grows, so do its impacts. Packaging is the major growth area in flexography, so decisions about ink systems used for printing of packaging will have a proportionally larger impact as the use of flexographic packaging expands. Also, because of the trend of mergers and acquisitions in the flexographic industry, individual firms grow in size and influence, so decisions about inks made by one company may have a greater effect. Decision-makers should be aware that they are capable of encouraging environmental improvements and moving their operation closer to environmental sustainability.

Because the use of flexographic inks is expected to continue growing, environmental impacts could grow as well. Although individual ink formulations studied in the CTSA contained widely varying numbers of chemical categories of concern, no ink system or formulation was found to be free of hazards or risks. In particular, specific formulations in systems that are often regarded as less harmful (i.e., water-based and UV-cured) are not necessarily more safe. As the CTSA shows, hazards and risks varied considerably among the systems, depending on solvent content and other factors.

There may be substantial opportunities to reformulate inks to reduce environmental and human health risks. For example, solvent-based printers need to keep oxidizers in prime working condition at all times. Printers using water-based inks without an oxidizer should select inks containing the lowest possible percentage of VOCs. And both solvent-and water-based printers can significantly reduce their energy requirements by recirculating warm air from dryers. To identify other opportunities to make improvements, printers and ink formulators should consider all aspects of inks, including performance characteristics, risks to facility workers and the environment, and costs.

Knowledge is key to improving inks and printing practices. The information in this CTSA can help printers and formulators identify potential hazards and risks present in some inks, as well as identifying possibly safer alternatives for some chemicals and chemical categories. Table ES.8 lists general methods for reducing potential hazards of and risks of working with inks that professionals working in or with the flexographic industry may wish to consider.

Table ES.8 Ways to Reduce Hazards and Risks Related to Flexographic Inks

Suggestion	Printers	Formulators	Other (Technology Assistance Providers, Colleges, etc.)
Read CTSA materials to become familiar with environmental and health impacts of chemicals in inks.	X	X	X
Select the cleanest inks that make business sense. Minimize use of hazardous inks.	X		
Minimize the need for and use of press-side solvents and other additives.	X	X	
Maximize good ventilation, particularly in the prep and press rooms.	X		
Ensure that all workers who handle inks wear butyl or nitrile gloves, to minimize exposure to chemicals.	X		
Ensure that all pollution control devices are maintained properly and work correctly at all times.	X		
Identify ways to improve operations and environmental performance by looking at all steps in the printing process throughout the facility.	X		X
Develop comprehensive safe working policies and practices for inks, and ensure that workers follow them.	X		X
Minimize the amount and number of hazardous ingredients in inks.		X	
Make environmental and health information about inks more accessible and understandable (e.g., expand MSDSs, provide best practice tips, include chemical information in sales materials).		X	
Support research on untested and inadequately tested flexographic ink chemicals, especially those with clear or possible risk concerns and those that are produced in high quantities (high production volume chemicals).	X	X	X